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A bioeconomic approach to derive economic values for pasture-based sheep genetic improvement programs[1]

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ABSTRACT: Economic values for a range of different maternal and carcass sheep performance traits were derived for hill sheep in the United Kingdom. A bioeconomic model that includes estimates of available energy supply and herbage intake for sheep from hill and mountain pastures, together with that from improved grassland, has provided a base from which to define the economic limitations to genetic improvement in harsh environments. The degree to which different farm systems can accommodate changes in animal performance as a result of genetic improvement was explored. Results showed that genetic improvement in harsh environments is likely to be of greater benefit to farms with fewer constraints to improvements in production, such as better quality pasture or a higher ratio of improved grassland to hill pasture. For farm types in the harshest locations, the economic value of improving litter size was only positive within defined production limits. Increasing litter size beyond these limits resulted in diminishing marginal returns because the costs of additional inputs outweighed the benefits of extra returns. Results also showed that relative improvements in maternal characteristics are at least as economically important as improvements in lamb carcass quality. The effects of variation in market prices on economic values for the major costs and returns of the sheep enterprises showed that, in general, economic values are robust. The methodology described could be adapted and applied to other extensive sheep systems worldwide.

Key Words: Animal Breeding, Extensive Production, Genetic Improvement, Sheep

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Introduction

Sheep breed improvement programs in the United Kingdom focus on combining several goal traits into an index of overall merit, as an aid to selecting parental and replacement stock. Goal traits are characteristics of an animal's performance (e.g., lamb weight or litter size) that a breeder wishes to improve or alter. Currently in the United Kingdom, this is done by weighting breeding values from BLUP analyses according to desired responses in each goal trait. This requires an investigation of the economic relativity of goal traits within typical production systems. Even within specific sectors of the U.K. sheep industry (e.g., the hill sheep sector), there is a wide range of different farm types and production levels.

Three typical hill farm types that have been defined in the United Kingdom (Eadie, 1985) are intensive, semi-intensive and extensive. These farm types represent differences in hill pasture quality, precipitation, topography, and the proportion of improved grassland relative to unimproved hill pastures. The economic value (**EV**) of each component of the breeding goal may differ considerably for the three farm systems as a result of the differing levels of productivity and the physical constraints of the farms themselves.

A model framework to derive economic values for pasture-based sheep systems has been developed and described by Conington (1999). In this model, available energy supply is estimated, and uptake for sheep from both indigenous and improved pastures is predicted and costs estimated appropriately to provide a base for deriving EV. The objectives of this study were to derive EV for a combination of carcass and maternal characteristics for U.K. hill sheep on the three typical hill farm systems described above.

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Materials and Methods

Hill Farm Type and Feed Availability

Three farm types were modeled to reflect the three main hill types (intensive, semi-intensive, and extensive). All three farms were assumed to have a 100-ewe purebred Scottish Blackface flock, but to differ significantly in the proportion of hill to improved grassland and quality of hill pasture (and hence hill stocking rate). The areas of the different vegetation communities for the three models are shown in Appendix Tables A1 to A3. The hill pastures on all three farms were assumed to be dominated by heather moorland (*Callunas vulgaris*), together with a range of other grass species. *Callunas vulgaris* is a woody shrub that is typical of vegetation found in hill and mountain regions of northwestern Europe. Conington (1999) described how results from a Hill Grazing Management Model (**HGMM**; Armstrong et al., 1997a,b) could be integrated into a wider, whole-farm model for the derivation of EV for pasture-based sheep systems. In this paper, the HGMM was used to predict DM production from different vegetation types specified on the three farm types described above, after adjusting for temperature zone, altitude, rainfall, rainfall retention, and fertilizer use. Seasonal changes in the quantity and digestibilities of the herbage intake by ewes and lambs were determined according to the monthly numbers and live weights of each class of stock grazing the hill.

The hill pasture vegetation mix and overall grazing quality characterized the different hill pastures. The intensive farm with the best quality pasture had a proportion of *Festuca agrostis* pasture in addition to heather, which itself includes a high proportion of *Festuca agrostis* within it. The other two farm types had less *Festuca agrostis* within the heather plant communities, and had poor-quality, *Nardus stricta*-dominated pasture as the main grassland area, with relatively low proportions of good-quality plant species within it.

Most hill farms in the British Isles have a range of different forages in their enclosed paddocks, from high-quality, recently reseeded forage to wetland of low agricultural value. It was assumed that the improved pastures comprised reseeded perennial ryegrass (*Lolium perenne*) because credible data on production and responses to nitrogen are available for this grass species. For each farm type (intensive, semi-intensive, and extensive), a "baseline" farm was created on which grazing resources and animal requirements were in balance with typical levels of feed and fertilizer to improved pastures. Inevitably, due to the complexity and variability of hill farm systems and of hill pastures, these baseline farms are unique. These results were then fed into a "whole-farm" simulation model described by Conington (1999) to provide the framework for the development of the three typical model farm types from which EV were then determined.

Feed Requirements

The requirements for total feed energy (in units of metabolizable energy) of sheep were calculated using the methods described by Conington (1999). The assumptions of key elements (e.g., ewe mature weight, lamb growth rate, etc.) used to determine energy requirements are shown in Table 1. Because these assumptions affect both the outputs and the inputs of the model (i.e., the assumptions of mature weight and lamb growth rate affect the availability of grass and supplementary feed required), they are summarized together with the other performance indicators of the model in this table. Details of lamb weights derived from the model and the major performance indicators for each farm system are also shown in Table 1. The data summarize the differences between the three sheep farm systems in the key areas of flock productivity.

Monthly estimates of the nutritional requirements reflected changing physiological needs for pregnancy, for loss and regain of BW in winter, and for the net costs of lactation and changing BW in the summer. Differences between the food energy available and that required were converted into supplementary feed energy requirements and then into monetary value. As the sheep in the baseline model were already receiving supplementary feed before lambing, marginal changes in requirements at this time were allocated to extra supplementary feed alone.

Flock Structure

Of critical importance to the model is the correct definition of flock structure. This was achieved by using Markov chain methodology (Agrawahl and Heady, 1972) to generate the ewe age structure, replacements required, and the number of lambs born alive per ewe according to the assumptions made about ewe survival and productivity. The age structure of model flocks was incorporated into the Markov chain, where each age group of ewes was represented by a row vector of states $\mathbf{S}(\mathrm{a})_{t=0}$, where a represents the number of ewes in each age group at time t. The number of ewes in $t_{1 \ldots 10}$ yr depends on the matrix of transition probabilities, $\mathbf{P}$, which describes the probability of survival from the state described by row i at time t, to the state described by column j at time $t + 1$. Because $\mathbf{P}$ is fixed for all values of t, the Markov chain is therefore static.

The assumptions of the proportions of productive ewes (excluding barren ewes and ewe deaths before lambing) and litter size were defined by diagonal matrices, also fixed for all values of t. The abbreviation $\mathbf{N}$ is a matrix of the proportion of productive ewes per age class on the diagonal, and zeros on the off diagonal, and $\mathbf{L}$ is a matrix with litter size per ewe age category

Table 1. Performance data of model farms

Performance trait	Intensive	Semi-intensive	Extensive
Ewes			
No. of ewes	100	100	100
Mature ewe weight, kg	57	53.5	50
Ewe death + cull rate, %	6.7	8.0	9.0
Barren, %	4.61	6.06	7.00
No. of nonproductive ewes[a]	6.59	8.39	9.60
Ewes lambing	93.41	91.61	90.39
No. lambs per ewe to ram	1.40	1.20	1.00
No. lambs per ewe lambing	1.51	1.31	1.11
No. lambs reared per ewe	1.21	1.05	0.89
No. lambs reared per ewe lambing	1.29	1.15	0.98
Lambs			
Single lambs lost	4.87	6.35	8.05
Twin lambs lost	12.84	8.32	2.89
Triplet lambs lost	1.74	0.35	0.19
Lambs for sale or keep	120.64	105.09	89.33
Female lambs kept for breeding	29.40	30.31	30.94
Male lambs kept for breeding	2	2	2
Lambs sold to other farms to be finished for slaughter	0	36.39	56.40
Lambs sold fat	89.23	36.39	0
Single male birth weight, kg	4.10	4.00	3.90
Twin male birth weight, kg	3.96	3.70	3.40
Triplet male birth weight, kg	3.60	3.00	2.70
Single male weaning weight, kg	30.79	28.01	26.33
Twin male weaning weight, kg	29.29	28.01	27.83
Triplet male weaning weight, kg	28.29	27.01	26.83
All lambs weaning weight, kg	28.89	27.05	25.66
Nonbreeding stock weaning weight, kg[b]	29.19	27.42	26.17
Mean carcass weight, kg	17.03	16.54	—
Mean age at weaning, d	119	119	119
Postweaning growth rate, g/d	120	120	—
Mean age at slaughter, d	218	214	—
Mx weaning weight[c]	0.85	0.83	0.8
Mx slaughter weight[d]	0.64	0.65	—
Carcass weight/lamb weight	0.43	0.43	0.43
Proportion of ewes sold for further breeding:ewes sold for fattening for slaughter[e]	0.25:0.65	0.25:0.65	0.25:0.65
Proportion of single:twin females kept for breeding	0.30:0.70	0.50:0.50	0.85:0.15

[a]Includes 0.25% of ewes that die before lambing.
[b]Non breeding stock are lambs not kept for breeding that are sold.
[c]Proportion of potential growth achieved for weaning weight.
[d]Proportion of potential growth achieved for slaughter weight.
[e]Ten percent of fourth-parity ewes are culled directly after weaning.

on the diagonal, and zeros on the off diagonal. The chain is then defined as:

$$\mathbf{S}(a)_{t+1} = \mathbf{P}\ \mathbf{S}(a)_t$$

and $\mathbf{NLS}(a)_t$ gives the number of lambs born for each age group (and thus a flock average) and the number of replacements needed each year. The steady state is reached before $t = 10$, and the final population structure was used in the gross margin calculations. Thus, this methodology provides information on the equilibrium flock structure, litter size, and replacement rate on which the model flock performance is based.

Lamb Birth Types

The numbers of single, twin, and triplet births were determined from the following equations, derived by equating the mean and variance of litter size to their expectations. The equation used for singles was $3 - 2.5\mu + 0.5\nu^2 + 0.5\sigma^2$. For twins, it was $4\mu - 3 - \mu^2 - \sigma^2$, and that for triplets was 1 − proportion singles − proportion twins, where μ = mean litter size per ewe lambing, and σ^2 = variance of litter size. A coefficient of variation of 0.36 (Fogarty, 1985) was assumed, giving $\sigma^2 = (0.36\mu)^2$. The distribution of litter size categories predicted from this method was compared with field data from the two different experimental hill farms described by Conington et al. (1995) to verify that the model predicted realistic proportions of each litter size as these flocks differed in average litter size by 0.3 lambs per ewe. Differences in litter size were assumed between dam age groups. These were determined in accordance with those observed on our experimental farms. For example, the litter sizes for 2-, 3-, 4-, and 5-yr-old ewes on the intensive farm were 1.30, 1.55, 1.60, and 1.57, respectively.

Lamb Live Weight and Carcass Weight

Lamb weights at a given age were derived using a form of the Gompertz (1825) growth equation with an additional multiplier, *Mx* (Amer et al., 1997), which allows for limiting growth conditions. The equation used in the model is as follows:

$$Wx = A \times \exp\{-\exp[G - B\,(t_2 - t_1)]\}$$

where Wx = lamb weight, A = mature weight, G = ln [–ln (bwt/A)], $B = 0.0365/A^{0.73} \times Mx$, Mx = proportion of potential growth achieved, and $t_2 - t_1$ = time from birth to weaning (or from weaning to slaughter for slaughter weight).

The values of Mx were altered for each farm system to produce lamb weights typical for each system, and based on average weights from Scottish Agricultural College experimental farms. Live weights were determined in this way for single male lambs, and a set of constants were used to derive weights for single females and for twins and triplets of both sexes. Information for male lambs is shown in Table 1. Differences between male and female weaning weights were adjusted by 1.89 kg, and for carcass weight it was 0.7 kg. Carcass weights were derived by scaling the assumed live weights by a proportion of 0.43.

Derivation of Economic Values

The EV were derived for each trait independently of the other breeding goal traits. For example, the EV for carcass weight was estimated without a correlated change in weaning weight, and vice versa. In this way, any double counting associated with such correlations are avoided. As the EV for several of the traits were not linear, they were calculated as the first derivative of the gross margin with respect to the goal trait of interest. This derivative was calculated from the quadratic curve fitting the gross margin when the goal trait was at the population mean and, with the exception of litter size, when the goal trait was increased and decreased by an increment of one genetic standard deviation. Smaller increments of a quarter genetic SD were made for litter size because of the impact that it had on the EV for the extensive farm system.

With the exception of carcass fat and conformation, EV for the goal traits were calculated at the mean performance levels, using gross margin calculations from the whole farm model. A full explanation of how EV for fat class and conformation score were calculated is given below. All EV were subsequently multiplied by a combined frequency of expression (discounted gene expression coefficient) to account for genetic improvements in traits being expressed at different times by a different number of animals, and to discount expected future returns to present values.

Breeding Goals

Ten breeding goal traits were considered for inclusion into selection indexes for hill sheep. The definitions of each trait, their importance in hill sheep breeding systems, their influence on other components of the farm system and methods of computing the economic values for each goal trait are described below. Genetic information for these traits is shown in Appendix Table A8 and is also published in Conington et al. (2001).

Mature Size. Premating live weight was used as the estimate of mature BW. For economic weight calculations, it was assumed that any differences among ewes for this trait were maintained throughout the year, and throughout the lifetime of the ewe. The mature weight for rams was assumed to be proportionally 0.4 higher than ewe mature weight (Hammond 1932). The indirect benefits from increasing mature size are heavier offspring, higher litter size, and heavier fleece. However, the only direct economic benefit of heavier ewes was increased cull ewe value. This ensures that no double counting is apparent, for example, due to higher litter size or heavier fleeces. The costs of having heavier ewes are the supplementary feed costs and extra fertilizer and rental of additional enclosed pasture. The costs of having heavier ewes are calculated annually, whereas the benefits of higher cull ewe values are only received once in a ewe's lifetime. The model assumes that of the number of ewes available after rearing their fourth parity, proportionally 0.25 are sold for further breeding, 0.65 to be fattened for slaughter, and 0.10 are culled directly. The payment for ewes sold for further breeding was on a "per ewe" basis (regardless of mature size), and for ewes sold for slaughter, payment was on a carcass weight basis. Prices used in the model for ewes sold for further breeding were the average price per ewe received in 1997 from a total of 20,547 Blackface ewes sold at two major ewe sales in Scotland. For ewes fattened for slaughter, the price per kilogram used in the model was the average price paid in 1997 by a leading cull ewe buyer and processor because such information is not collected through the normal price-reporting channels (to the Meat and Livestock Commission, **MLC**).

Longevity. Longevity was defined as the age of a ewe when it leaves the flock. It is affected by a combination of culling policies and ewe death rates (often termed "voluntary" and "involuntary" culling, respectively) and influences the number and cost of replacements required to maintain the flock size. Increased longevity results in 1) increased average age of the flock, thereby reducing the number of replacements required each year; 2) having more ewes available for sale at the end of their fourth parity, with an increase in the number of ewes suitable for selling for further breeding vs. selling them directly for slaughter; 3) having more ewe lambs to sell, although the cull ewes will have a lower value per ewe than younger cull ewes; and 4) higher productivity from a slightly older flock age profile. The decrease in death and cull rates for all ewe age groups (including replacement females) and a reduction in the number of replacements required contribute to improved flock profitability. A reduction in veterinary and medicine costs was computed due to a lower number of replacements being kept, rather than from having healthier ewes per se. A benefit for grass growth is also seen due to a reduction in the demand for hill grazing, which would be cumulative over time. This could result either in some land becoming available for alternative use, such as for hill cattle grazing, or in it being left to enhance the biodiversity of the hill pasture. The costs of improved longevity are marginally higher feed costs per ewe from keeping a mature ewe vs. a replacement female, higher feed costs from higher average litter size, and a lower wool clip value from mature vs. replacement female fleece. The proportion of animals within each age group that became productive ewes the following year was increased in the Markov chain to measure the impact of improved longevity on flock performance. A constant barren rate was assumed for each farm model.

Number of Lambs Reared. The number of lambs reared was defined as the number of the ewe's own lambs reared until weaning. It is influenced both by the litter size born and survival rate of lambs. Changes in litter size alter the proportions of ewes rearing litters of singles, twins, and triplets, which in turn influences both the number of lambs sold and the costs and revenues of lambs sold per ewe lambing. In U.K. hill farms, twin lambs are usually reared on improved pastures and single lambs on the native grasslands. Changes in the number of lambs reared were made by increasing litter size for each ewe age group in the Markov Chain calculations, while holding survival rates for each birth type constant. The benefit of increasing the number of lambs is higher financial return from the sale of more lambs. The costs of increasing the number of lambs reared are mainly ewe feed, forage, and extra veterinary and medicine costs. Supplementary feed to meet these additional requirements in late pregnancy has to be bought in, increasing the cost of having twin-bearing ewes. The background to the forage calculations is described above, but the model assumes any increase in the demands for grass from the improved forages, above that provided from a maximum input of 150 kg nitrogen per hectare, is met by rented grazing.

Lamb Loss. Lamb loss is the number of a ewe's lambs born (including dead lambs and those transferred to other ewes) minus the number of lambs reared. The proportion of lambs lost before being sold was different according to litter size. This proportion was 0.10 for all single lambs, 0.15 for twins, and 0.30 for triplets. These were altered to 0.11, 0.16, and 0.31 (and 0.09, 0.14, and 0.29), respectively, for the derivation of the economic value for lamb loss. Improving lamb losses incurs no additional winter feed costs, unlike increasing the number of lambs per ewe mated. The benefit of reducing lamb losses is increased number of lambs available for sale after weaning. The grazing and medicine costs associated with higher lamb numbers are included in the calculations.

Maternal Component of Weaning Weight. Maternal weaning weight is defined as the average weight of lambs weaned per ewe, including those transferred from other ewes. The importance of this trait is to identify ewes with a higher milk supply, as measured indirectly through the weight of lambs weaned. The costs of increasing this trait were calculated by increasing ewe milk supply to meet the same proportion of lamb requirements as that before the incremental change in weaning weight. For example, twin ewes grazing enclosed pasture on the extensive farm produce on average of 2.25 L/d of milk (AFRC, 1993) at the peak of lactation in early June, which meets 57% of lambs' requirements. Increasing average lamb weaning weight by 0.5 kg required an increase in milk production to 2.29 L/d at this stage of lactation. The benefits of ewes with higher milk production are heavier lambs at weaning. However, the consequential costs of having heavier lambs at weaning were not included here to avoid double counting the inevitable costs incurred as a direct result of having heavier lambs. For lambs sold for finishing on other farms, heavier lamb weights equate directly to higher lamb value. For finishing lambs, this means a shorter finishing time to achieve the same carcass weight, with a consequent reduction in lamb finishing feed costs.

Fleece Weight. In the United Kingdom, the main influences on wool price within a breed are fleece weight and freedom from contamination, such as vegetable matter and sprays. Although the quality affects price, there is no consistent trend in prices received across years for fleeces that differ in the degree of kemp and gray fibers. Importantly, the price premiums for improved quality are smaller than if the fleece was simply free from contamination. Hence, the EV was derived for fleece weight only. There are no direct costs associated with increasing fleece weight as there is no strong evidence to suggest there are significant increases in feed requirements with improved genetic potential for wool production at a constant ewe BW (Elliott and Johnson, 1976; Morris, 1980; Binnie and Clarke, 1992; Clarke and Rae, 1997). The benefit is the additional revenue from extra weight of fleece sold.

Weaning Weight (Direct). This is defined as the weight of lamb at a constant weaning age. Whether lambs are sold to other farmers to be finished for slaughter or finished on the farm of origin, heavier weaning weights are beneficial. The EV of heavier weaning weights, for lambs finished to slaughter weights, were calculated at a constant carcass weight for the intensive and semi-intensive farm types. In this way, double counting the benefits of heavier weaning weights, heavier carcasses, and heavier mature ewes is avoided. Also, the EV between farm systems are assessed on an equitable basis. The benefit to the producer who sells lambs to other farmers to be finished for slaughter is heavier weaning weights and hence greater lamb value. The benefit to the semi-intensive and intensive farm systems is the savings in feed costs from a reduced number of days to slaughter. The cost of heavier lambs at weaning is higher preweaning feed cost. Specifically, the costs for each system are computed as extra fertilizer requirements, marginal increments for administering anthelmintics to heavier lambs before weaning, and (for the semi-intensive and intensive systems) the additional "cost" of buying heavier lambs back into the farm to finish.

Carcass Weight. The benefit of heavier carcasses is greater value per lamb. The costs of heavier carcasses are the feed costs incurred from extra time required to finish lambs to a heavier weight, and thus extra postweaning demands on grazing. This is because when animals are selected to be leaner at a given age (e.g., at weaning), it theoretically takes them longer to finish to a given level of fatness. This is because they are biologically less mature at the fixed age. In practice, both live weight and body composition traits are usually in the breeding objective, so the additional days required to reach the point of slaughter from being leaner at a given age is counterbalanced by having faster-growing animals. Therefore, the calculation of the benefits of heavier carcasses was made at a constant weaning and mature weight within each system, to avoid double counting the benefits and costs of having heavier weaning weights and higher mature weights. The number of extra days to finish (at the same preincrement growth rate) was subsequently multiplied by the daily cost of finishing lambs. The average market price for the marketing season August to December from 1993 through to 1997 (£2.1743 per kilogram of carcass weight) was used in the model.

Carcass Conformation Score and Fat Class. For most lamb payment schemes in the United Kingdom, MLC conformation score and MLC fat class influence lamb price to a much lesser degree than the weight of the carcass or the time of marketing (Conington et al., 1998). Improving fat and conformation at a fixed weight do not have associated impacts on other components of the sheep farming system (or at least within-breed improvements by traditional selection are unlikely to have any major impact), with the possible exception of a very small reduction in feed cost following selection for reduced fatness (Conington, 1999).

A different approach was required to derive EV for these traits because the pricing system is categorical, with implied thresholds, and MLC fat class has intermediate optima. The EV for fat class and conformation were therefore calculated using the method described by Hovenier et al. (1993). A threshold model with a mean = 0 and SD = 1 was assumed (P. R. Amer, personal communication, Abacus Biotech, New Zealand) using Mathcad 6.0 (Mathsoft Inc., Cambridge, MA) to calculate the underlying fat and conformation distributions from the price schedule and proportions of lambs falling into each carcass category. Fat class data were transformed to their corresponding estimated s.c. fat proportions (**ESF**) before analysis: fat class 1 = 0.04, class 2 = 0.08, class 3L = 0.11, class 3H = 0.13, class 4L = 0.15, class 4H = 0.17, and class 5 = 0.20 (Kempster et al., 1986). Penalties and premiums for fat and conformation were calculated independently. The premiums and penalties for fat class were calculated at a constant conformation score and carcass weight, and those for condition score were calculated at a constant fat class and carcass weight. The premiums and penalties are shown in Appendix Table A7, and a detailed description of how they were calculated is given by Conington (1999). In short, price premium/penalties for fat class and conformation score were collated from the average of six separate pricing schedules operating in 1998. The proportions of lambs in each fat class and conformation class cell were based on data from 992 Blackface lamb carcasses classified from lambs from two Scottish Agricultural College experimental hill farms born in 1991 and 1992. Together, these data provided information to determine the independent weighted premiums and penalties of fat and conformation scores, and the original "base" threshold values on the underlying normal distribution scale for the derivation of each EV. These EV were regressed on the incremental change, and the first derivative was taken as the EV.

Gene Flow. Genetic improvements in different traits are expressed at different times by different numbers of animals. For example, females older than 2 yr express litter size every year, whereas longevity is only expressed once in the animal's lifetime. Accounting for the flow of genes across time through the flock overcomes this problem when deriving economic values. Gene flow (or Markov chain) methodology (Hill, 1974) was used in this study to count the expression of genes across years. Total expression of each category of traits was achieved by multiplying the vector of gene distribution at each time point by a vector describing the expression of the trait category by each age class. To compare all trait categories in an equitable way, the expressions of the benefits were counted across years, discounted appropriately and then summed to get a discounted gene expression coefficient.

The genetic superiority for the following categories of traits is expressed at different times: 1) lamb performance, 2) maternal performance, 3) wool and mature weight, and 4) longevity. Assumptions on timing and number of expressions are detailed in the following sections.

Lamb Performance Traits. These traits are expressed once only by all yr-1 lambs destined for slaughter. Also, half the genetic superiority expressed once by slaughter progeny of daughters is expressed, but this occurs from yr 3 to 6. A quarter of the genetic superiority expressed once by slaughter grand-progeny of females, from yr 5 to 12, etc., are included.

Table 2. Economic values for the three farm systems, discounted gene coefficient (DGC), and the economic weight for each goal trait

	Economic values per 100-ewe flock				Economic weights per 100-ewe flock[a]		
Trait	Extensive	Semi-intensive	Intensive	DGC	Extensive	Semi-intensive	Intensive
Mature weight, £/kg	−10.37	−13.57	−11.84	1.3769	−14.28	−18.68	−16.30
Longevity, £/d	5.42	6.19	6.82	0.3032	1.64	1.88	2.067
No. reared, £/lamb[b]	16.94	17.46	27.08	1.3323	22.57	23.27	36.08
No. lost, £/lamb[c]	−22.04	−27.02	−31.99	1.3323	−29.37	−35.99	−42.62
Average weaning wt, £/kg[d]	50.28	52.67	54.09	1.3323	66.99	70.17	72.06
Fleece weight, £/g	0.12	0.12	0.12	1.3769	0.17	0.17	0.17
Weaning weight, £/kg	43.88	50.21	55.02	1.6164	70.92	81.15	88.93
Carcass weight, £/kg	—	20.00	76.29	1.6164	—	32.33	123.31
Fat class, £/ESF[e]	—	−7.89	−19.95	1.6164	—	−12.76	−32.25
Conformation, £/unit	—	31.32	78.89	1.6164	—	50.62	127.53

[a]Economic weight is DGC multiplied by the economic value.
[b]For example, increasing the number of lambs weaned per 100-ewe flock from 120 to 121.
[c]For example, increasing the number of lambs lost per 100-ewe flock from 13 to 14.
[d]Total weight of lambs reared per ewe.
[e]For example, increasing estimated subcutaneous fat proportion (ESF) from 0.10 to 0.11.

Litter Size, Lambs Lost, Maternal Weaning Weight. These are expressed by first-parity ewes in yr 3, second-parity ewes in yr 4, third-parity ewes in yr 5, and fourth-parity ewes in yr 6. Thus, each ewe gets up to four opportunities to express maternal traits, but each year, only a proportion of the flock expresses the genetic superiority resulting from selection and use of this team of ram lambs as sires. In addition, half of the genetic superiority expressed by first-, second-, third-, and fourth-parity ewes that are daughters of original females, in yr 3 to 6, are included.

Fleece Weight and Mature Weight. The pattern is similar to that for maternal traits, but their expression starts 1 yr earlier.

Longevity. Longevity is expressed once per ewe, with the subsequent normal flow of genes through the population. It was assumed that it was expressed at the mean flock age.

Discounting. Economic benefits promised in the distant future are perceived to be of lesser value than benefits immediately available. Future benefits are commonly discounted to take account of this time effect. Assuming a discount rate of $x = 0.05$, future benefits occurring in year t are scaled by $1/(1 + x)^t$ to express them as current values (Weller, 1994).

Sensitivity Analyses. The sensitivity of the EV to changes in the main sources of returns (e.g., prices of lambs sold to other farmers to be finished for slaughter and those finished on the farm, ewes sold for breeding, cull ewes, and wool) and the major costs of production (e.g., lamb finishing feed, ewe feed, and fertilizer) were investigated. Each price was changed by proportional increments of ±0.5 around the prices used in the base models because costs and returns for agricultural commodities are frequently subject to considerable price fluctuations (Weller, 1994). New "base" gross margins were calculated after each single price change, and new EV were then calculated as above.

Results

Gross Margins

The main differences among the three farm types form the base for the gross margin calculations. The gross margins produced from the model for the three farms are consistent with acceptable performance indicators for each category of hill farm (SAC, 1997), as shown in Appendix Tables A4 to A6.

Gene Flow

The discounted gene expression coefficients from the gene flow analyses are the same for all lamb performance traits at 1.6164 and maternal traits at 1.3323. As measurements of wool and mature weight occur once per year, the coefficient for these traits is 1.3769. Longevity is only expressed once in an animal's lifetime, and hence it is lower at 0.3032.

Economic Values

Economic values, discounted gene expression coefficients, and economic weights for all 10 goal traits for the three farm systems are shown in Table 2. In general, the EV for the intensive farm are higher than those for the less intensive farming systems, although the comparison varies for different traits. This means that genetic improvement in harsh environments is likely to be of greater benefit to farms with fewer constraints to improvements in production, such as better quality pasture or a higher ratio of improved grassland to hill pasture. The results show that the main influences on overall productivity are lamb output (number of lambs reared), lamb survival, and the weight of these lambs at the point of marketing, which is in common with most sheep enterprises in the United Kingdom.

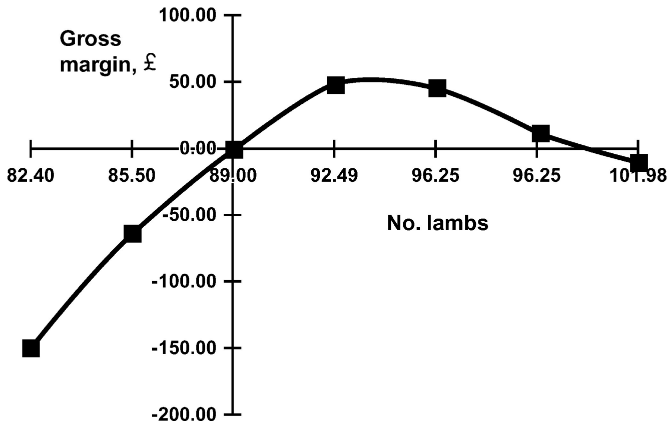

Figure 1. Change in gross margin as the number of lambs reared changes, for the extensive farm.

Taking increments above and below the mean for each trait has shown that the EV are not linear for all levels of production. In the case of number of lambs reared on an extensive farm, the nonlinearity in EV for this trait is even more extreme. There is a benefit to small increases in litter size. However, this benefit tapers off and becomes a net loss as the number of lambs increases above an extra 0.3 lambs/ewe. Clearly, in such a situation, the economic weight for the trait depends on the current population mean. For the intensive farm, the benefits of increasing the number of lambs reared do not increase at a linear rate beyond 1 SD (0.13 lambs). These results are illustrated in Figures 1 and 2.

The EV for fat class is £–19.95 per unit increase in ESF per 100-ewe flock. For conformation score, the same figure is £78.9. The results show that the premium for an increase in a unit conformation score is roughly equivalent to the penalty for increasing fatness by a whole fat class (as each fat class represents four ESF units; Kempster et al., 1986).

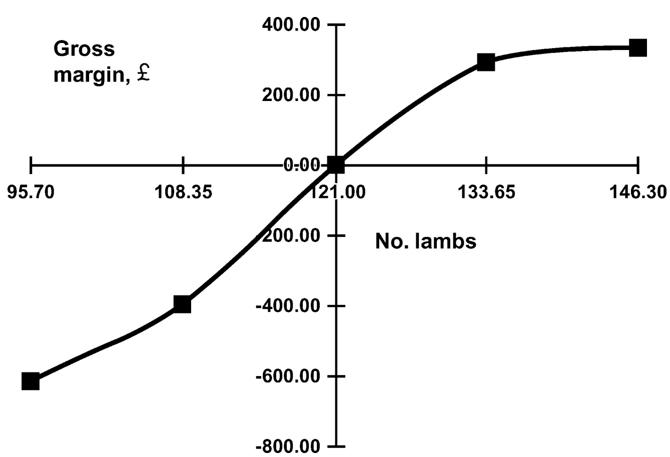

Figure 2. Change in gross margin as the number of lambs reared changes, for the intensive farm.

Sensitivity Analyses

The price sensitivities for the intensive farm are shown in Table 3. In general, the EV are robust to fluctuations in prices that do not have a significant impact on, or which are not affected directly by, the trait in question. For example, the EV for mature weight for the intensive system remains within proportionally 0.97 of the original EV for changes in prices for lambs, wool, lamb finishing feed, and fertilizer. However, it decreases or increases by proportionally 0.29 when the price of ewes sold for slaughter is reduced or increased by proportionally 0.5. The same pattern can be seen for ewe feed prices. The EV of mature weight is less negative (by proportionally 0.66) when the cost of ewe feed decreases by proportionately 0.5 to £0.074 per MJ. The negative EV for carcass weight when the price of lambs is very low shows that increasing carcass weight is only profitable if a corresponding reduction in finishing costs is made. These results imply that unless one of the major component prices changes dramatically, the EV are stable. If prices do change significantly, then new EV will be required.

Discussion

The methods described in this paper combine modern approaches for the derivation of EV for conventional production traits, traits with payments based on thresholds, and those with an economic optimal value. Potentially, this method can provide realistic, physical limitations to the effect of genetic improvement programs in extensive environments. Few other whole-farm models have been reported for sheep for the purpose of deriving EV (Wang and Dickerson, 1991; Amer et al., 1999), and they have not incorporated estimates of energy supplied by grazing pastures. However, Visscher et al. (1994) derived EV for dairy traits with fixed energy supply and requirements, although the contribution of energy supplied from grass was not differentiated from that of concentrates. Also, no account of seasonal grass growth or forage production was included in the calculations. The methodology used in this paper would be applicable to other sheep systems in different countries if minor modifications are made relating to indigenous grass species, sheep genotypes, and the relevant production systems.

Using Markov-chain methods to model flock structure over a given time period allows examination of the long-term effects that different litter sizes, barren rates, and ewe and lamb survival rates have on the number of replacements available and required. We have used expectations, given the mean and variance of litter size, to determine the number of single, twin, and triplet births within the model, as this is (by definition) consistent with field data. Amer et al. (1999) used probability theory from Hanrahan (1979) and

Table 3. Sensitivities of the economic values to price changes of key costs and returns for the intensive farm system

Price changes	Lambs reared	Lambs lost	Mature weight	Longevity	Fleece weight	Maternal weaning weight	Direct weaning weight	Carcass weight
Base values[a]	27.08	–31.99	–11.84	6.82	0.12	54.09	55.02	76.29
Lamb price, £/kg								
1.1 (slaughter), 0.45 (sold for finishing)	8.89	–13.15	–11.85	4.39	0.12	50.253	51.45	–11.44
3.3 (slaughter), 1.35 (sold for finishing)	45.28	–50.41	–11.85	9.23	0.12	57.647	58.59	164.05
Ewes for breeding								
23 £/ewe	27.08	–31.59	–11.5	6.44	0.12	59.068	57.30	76.30
70 £/ewe	27.16	–31.79	–11.85	7.17	0.12	54.095	57.30	76.30
Cull ewes, £/kg live wt								
0.25	27.08	–31.78	–15.32	6.24	0.12	54.095	57.30	76.30
0.75	27.08	–31.78	–8.38	7.39	0.12	54.095	57.30	76.30
Wool, £/kg								
0.48	27.08	–31.78	–11.85	6.81	0.06	54.095	57.30	76.30
1.44	27.08	–31.78	–11.85	6.82	0.19	54.095	57.30	76.30
Ewe feed, £/MJ								
0.077	25.79	–31.07	–4.05	6.86	0.12	51.009	49.37	76.30
0.022	28.43	–32.52	–20.03	6.76	0.12	57.329	60.93	76.30
Lamb finish feed, £/lamb/d								
0.025	29.79	–34.51	–11.85	7.18	0.12	30.834	31.76	130.40
0.075	25.27	–29.96	–11.85	6.58	0.12	69.614	70.53	40.23
Fertilizer								
N21,P20.5,K11.5	31.50	–32.23	–11.58	6.94	0.12	56.058	58.62	76.30
N63,P61.5,K34.5	22.63	–31.33	–12.03	6.69	0.12	52.13	51.42	76.30

[a]£/100-ewe flock.

principles of binomial distribution to estimate the proportion of ewes in each litter size category. Wang and Dickerson (1991) based their distributions of litter size as quadratic functions of the number born, and adjusted for deviations from normal ewe BW at the time of mating. This multidisciplinary model allows the detailed sensitivity analyses of changes in the base prices for the major costs and returns of the sheep farm system to be examined. In addition, these methods allow the consequential effects of changing each component individually to be encapsulated into a single gross margin.

To improve prolificacy, the emphasis for selection could potentially be moved away from improving litter size toward the ability of the ewe to rear the lambs that she gives birth to. Depending on which animal populations are under selection, this would depend on the additive genetic variation for this trait and its correlations with other traits in the breeding objective. Two breeding goal traits, minimizing the numbers of lambs "lost" and maximizing the number of lambs reared, have been included. By separating these two traits that are closely associated with each other, this enables a clear distinction between the biological effects of fecundity and lamb survival to be made, as well as correct attribution of costs associated with these components. Selection for these traits will ensure that dams of higher prolificacy will also have the ability to rear and nurture their lambs. This should lead to more sustainable breeding practices for hill sheep, which frequently suffer high neonatal losses.

The EV reflect the importance of maternal characteristics of purebred hill sheep, as well as carcass traits. Improving fleece weight in hill sheep is not considered a priority in the current economic climate in the United Kingdom. Including fleece weight in the breeding goal may be more important to producers of other hill breeds in the United Kingdom, such as the Cheviot or Shetland, or to flocks with lower-than-average lamb production because wool has a higher relative economic contribution to overall flock profitability. However, wool as a source of income to a hill flock is produced each year by every adult sheep, and is positively correlated with mature size. This means that allowing mature size to increase will result in a correlated increase in fleece weight. Compared with the other goal traits, the relative EV of fleece weight is greater in the extensive flock than the intensive flock, although the absolute value is the same. Although commonplace for dual-purpose and wool breeds in New Zealand and Australia, recording fleece weight in the United Kingdom is likely to be unpopular with breeders because of the low value of the fleece and the extra effort involved at shearing. However, the purpose of estimating the EV independently of each other (to avoid double counting costs and returns) is in the context of multitrait BLUP analyses, where the relationships among all of the traits are already accounted for through their correlations. If one or more of the traits were not included in the breeding goal (e.g., fleece weight), then the EV for correlated traits (e.g., mature size) would need to be altered to account for this.

The negative values for mature size on all three farming systems indicate that the costs of increasing mature size outweigh the benefits. However, as mature weight is positively correlated both phenotypically and genetically with live weight at weaning, mature weight is expected to increase following index selection (Conington et al., 2001).

Investigating changes in EV over a wide range of litter sizes has illustrated that there are "optimal" increments for some traits, beyond which the EV declines, resulting in diminishing marginal returns from genetic improvement, at least for the extensive farm system. The economic benefit of increasing the number of lambs reared in the extensive farm situation is negative when the increase in the number of lambs reared is too large because the cost of additional inputs outweighs the benefits of extra returns. This leads us to conclude that the performance of breeding flocks should be regularly evaluated and, if necessary, the EV recalculated to reflect the true level of performance of the flock. This would more accurately assess the economic impact of continuing to select for such traits when farm resources are limited.

Detailed analyses of theoretical "optimal" performance levels could be examined for each goal trait. Such analyses would provide further insight to determine "suggested production limits" for individual farm systems. This would facilitate the tailoring of economic indexes for hill breeds to suit different farming systems operating in different environments. Conington et al. (2001) describes three such selection indexes for this purpose. In Australia, where there are also large environmental differences between flocks, personalized breeding objectives are made for individual merino breeders to help them with selection decisions using OBJECT, a computer program to predict the likely rates of genetic progress for alternative selection criteria and EV (Atkins et al., 1994). In the United Kingdom, different indexes are largely confined to different breeds, which in turn largely represent different geographical areas. However, results from this study show that EV can differ according to different farming systems with the same breed.

Implications

This work has provided a base from which to define the economic limitations to genetic improvement in harsh environments for sheep. Genetic improvement in harsh environments is likely to be of greater benefit to farms with fewer constraints to improvements in production, such as better-quality hill grazing land. For farms in the harshest locations, the economic value of improving litter size was only positive within defined production limits. There is little economic reward to genetic improvement programs beyond these limits because the cost of production outweighs the benefits of extra financial returns. An application of this generic methodology would be for animal production systems where environmental factors play a major role in the suitability of different genotypes, such as in tropical, or arid and semiarid systems. It is important in such situations to model the true importance of each trait, the implications of changing the environment, and of changing the genotypes.

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Appendix

Table A1. Description and areas of vegetation types for intensive farm system

Vegetation community	Area, ha	Heather cover (*Calluna vulgaris*), %	*Fescue agrostis* in heather, %
Newly burnt heather[a]	5	—	30
Pioneer heather[b]	5	55	45
Building heather[c]	5	85	15
Mature heather[d]	5	95	0
Fescue agrostis	2	0	—
Reseeded grazing area[e]	5	—	—

[a]Heather (*Calluna vulgaris*) that has been burnt in the same year as the grazing season. This is typical for heather management in the moorlands of Scotland and northern England as heather is managed primarily for the game bird, grouse (*Lagopus lagopus*).
[b]Pioneer heather is less than 15 cm.
[c]Building heather is 15 to 30 cm.
[d]Mature heather is 31 to 40 cm.
[e]Reseeded grazing area is grazing land that has been reseeded with *Lolium perennae*, perennial ryegrass.

Table A2. Description and areas of vegetation types for semi-intensive farm system

Vegetation community	Area, ha	Heather cover, %	*Fescue agrostis* in Heather/Nardus, %
Newly burnt heather[a]	7.5	—	20
Pioneer heather	7.5	55	30
Building heather	7.5	85	10
Mature heather	7.5	95	0
Nardus dominated[b]	10	—	15
Reseeded grazing area	3	—	—

[a]See footnotes to Table A1 for a description of the different stages of heather growth.
[b]Nardus is a coarse grass species of low nutritional value typical of mountain grazing areas in Scotland.

Table A3. Description and areas of vegetation types for extensive farm system

Vegetation community	Area, ha	Heather cover, %	*Fescue agrostis* in Heather/Nardus, %
Newly burnt heather[a]	15	—	20
Pioneer heather	15	55	30
Building heather	15	85	10
Mature heather	15	95	0
Nardus dominated	20	—	15
Reseeded grazing area	1	—	—

[a]See footnotes to Table A1 for a description of the different stages of heather growth and Table A2 for the description of Nardus.

Table A4. Extensive farm gross margin per 100-ewe flock[a]

Gross output	Number	Prices, £	Per animal	Total £
	Lamb sales			
Slaughter				
Males	0	2.2	0.00	0.00
Females	0	2.2	0.00	0.00
Sold for finishing				
Males	42.67	0.9	23.57	1,022.27
Females	13.73	0.9	22.35	306.92
Valuation of lambs kept for finishing	0	0.9		0.00
Total lamb sales				1,329.20
	Ewe sales			
Breeding ewe	5.03	47		236.62
Sold for slaughter	13.09	0.5	25	327.24
Total ewe sales				563.85
	Wool sales			
Ewes	94.4	0.96		167.70
Ewe lambs	29.7	0.96		58.48
Total wool sales				226.18
	Subsidies			
Compensatory allowance	100	5.75		575
Annual premium	100	11.5		1,150
Less favored area supplement	100	5.35		535
Total subsidies				2,260
Less replacement (rams)	1	240		–240
Total output				4,139.23
	Variable costs			
Feed				
Bought in (ewes + rams)			2.54	253.78
Lambs (slaughter)	0	5.005	0	0
Forage net cost			0.238	23.791
Veterinary, medicine, dip			3.17	317.28
Haulage	5.03	1	0.05	5.03
Breeding ewes	13.09	1	0.13	13.09
Ewes for slaughter	30.93	3	0.93	92.81
Ewe lambs	30.93	12	3.71	371.23
Ewe lamb wintering costs				
Shearing				
Ewe lambs	30.93	0.6	0.19	18.56
Ewes	94.42	0.45	0.42	42.49
Rams	2	0.6	0.01	1.20
Miscellaneous				
Ewes	94.42	0.25	0.24	23.61
Lambs	89.33	0.5	0.45	44.67
Total variable costs			12.08	1,207.54
Gross margin				2,931.69

[a]Gross margin is defined as the total financial returns minus the total variable costs of production (i.e., ignoring fixed costs such as investment in capital). The gross margin is for one complete financial year.

Table A5. Semi-intensive farm gross margin per 100-ewe flock[a]

Gross output	Number	Prices, £	Per animal	Total, £
	Lamb sales			
Slaughter				
Males	25.27	2.2	36.85	931.1
Females	11.11	2.2	35.31	392.4
Sold for finishing				
Males	25.27	0.9	24.68	636.67
Females	11.11	0.9	23.49	261.02
Valuation of lambs kept for finishing	36.38	0.9	24.67	897.69
Total lamb sales				1,795.38
	Ewe sales			
Breeding ewe	5.17	47	—	242.88
Sold for slaughter	13.44	0.5	26.75	359.41
Total ewe sales				602.29
	Wool sales			
Ewes	95.01	0.96	—	168.74
Ewe lambs	29.15	0.96	—	57.38
Total wool sales				226.12
	Subsidies			
Compensatory allowance	100	5.75	—	575
Annual premium	100	11.5	—	1,150
Less favored area supplement	100	5.35	—	535
Total subsidies				2,260
Less replacement (rams)	1	240	—	–240
Total output	—	—	—	4,643.78
Variable costs				
Feed				
Bought in (ewes + rams)	—	—	4.33	432.58
Lambs (slaughter)	36.38	5.005	1.82	182.08
Forage net cost	—	—	0.60	60.12
Veterinary, medicine, dip	—	—	3.53	352.93
Haulage				
Breeding ewes	5.17	1	0.05	5.17
Ewes for slaughter	13.44	1	0.13	13.44
Ewe lambs	30.13	3	0.91	90.92
Ewe lamb wintering costs	30.31	12	3.64	363.69
Shearing				
Ewe lambs	30.31	0.6	0.18	18.18
Ewes	95.01	0.45	0.43	42.75
Rams	2	0.6	0.012	1.2
Miscellaneous				
Ewes	95.01	0.25	0.24	23.75
Lambs	105.07	0.5	0.53	52.53
Total variable costs	—	—	14.57	1,457.27
Gross margin	—	—	—	3,186.51
Finished lamb gross margin[b]				
Lamb purchase	36.38	0.9	24.67	897.69
Lamb feed	36.38	0.055	5.005	182.08
Lamb sales	36.38	2.20		1,323.50
Margin				243.74

[a]Gross margin is defined as the total financial returns minus the total variable costs of production (i.e., ignoring fixed costs such as investment in capital). The gross margin is for one complete financial year.

[b]Finished lamb gross margin takes into account the additional costs and revenue associated with finishing lambs on the farm of origin. If the two margins are added together, then a true picture can be made of the total gross margin associated with one year's lamb production.

Table A6. Intensive farm gross margin per 100-ewe flock[a]

Gross output	Number	Prices, £	Per animal	Total, £
	Lamb sales			
Slaughter				
Males	58.32	2.2	38.00	2,216.18
Females	30.90	2.2	36.50	1,128.04
Sold for finishing				
Males	0	0.9	26.23	0.00
Females	0	0.9	25.18	0.00
Valuation of lambs kept for finishing	89.23	0.9	26.23	2,340.83
Total lamb sales				2,340.83
	Ewe sales			
Breeding ewe	5.33	47	—	250.62
Sold for slaughter	13.86	0.5	28.5	395.12
Total ewe sales				645.74
	Wool sales			
Ewes	95.80	0.96	—	170.14
Ewe lambs	28.45	0.96	—	56.01
Total wool sales				226.15
	Subsidies			
Compensatory allowance	100	5.75	—	575
Annual premium	100	11.5	—	1,150
Less favored area supplement	100	5.35	—	535
Total subsidies				2,260
Less replacement (rams)	1	240	—	–240
Total output	—	—	—	5,232.72
Variable costs				
Feed				
Bought in (ewes + rams)	—	—	4.72	471.81
Lambs (slaughter)	89.23	5.005	4.47	446.58
Forage net cost	—	—	0.95	94.61
Veterinary, medicine, dip	—	—	3.99	399.37
Haulage				
Breeding ewes	5.33	1	0.05	5.33
Ewes for slaughter	13.86	1	0.14	13.86
Ewe lambs	29.42	3	0.88	88.25
Ewe lamb wintering costs	29.42	12	3.53	353.01
Shearing				
Ewe lambs	29.42	0.6	0.18	17.65
Ewes	95.80	0.45	0.43	43.11
Rams	2	0.6	0.012	1.2
Miscellaneous				
Ewes	95.80	0.25	0.24	23.75
Lambs	120.64	0.5	0.60	60.32
Total variable costs	—	—	15.72	1,572.47
Gross margin	—	—	—	3,660.24
Finished lamb gross margin[b]				
Lamb purchase	89.23	0.9	26.23	2,340.83
Lamb feed	89.23	0.055	5.005	446.58
Lamb sales	89.23	2.20	—	3,344.22
Margin				556.81

[a]Gross margin is defined as the total financial returns minus the total variable costs of production, (i.e., ignoring fixed costs, such as investment in capital). The gross margin is for one complete financial year.

[b]Finished lamb gross margin takes into account the additional costs and revenue associated with finishing lambs on the farm of origin. If the two margins are added together, then a true picture can be made of the total gross margin associated with one year's lamb production.

Table A7. Price premiums and penalties (£/kg) according to fat class and conformation score

Conformation[b]	Fat class[a] 1	2	3L	3H	4L	4H	5
E	–0.300	+0.099	+0.099	+0.0005	–0.175	–0.367	–0.483
U	–0.308	+0.074	0.074	–0.0078	–0.175	–0.367	–0.483
R	–0.316	+0.015	+0.024	–0.026	–0.175	–0.367	–0.483
O	–0.383	–0.051	–0.026	–0.137	–0.317	–0.367	–0.483
P	–0.433	–0.433	–0.433	–0.433	–0.433	–0.433	–0.483

[a]Fat class is assessed at the abattoir by trained operators according to the estimated subcutaneous fat proportions, where: fat class 1 = 0.04; class 2 = 0.08; class 3L = 0.11; class 3H = 0.13; class 4L = 0.15; class 4H = 0.17; and class 5 = 0.20 (Kempster et al., 1986).

[b]Conformation is assessed at the same time at the abattoir as fat class. It is a visual assessment of body shape to indicate body composition. E = excellent, U = above average, R = average, O = below average, and P = poor.

Table A8. Heritabilities (h^2) and genetic standard deviations (σ_g) for breeding goal traits

Trait	h^2	σ_g
Mature size, kg	0.47	3.17
Longevity, d	0.08	320
Lamb loss, lambs/ewe	0.03	0.09
No. weaned, lambs/ewe	0.07	0.12
Average weaning weight, kg	0.10	2.34
Fleece weight, kg	0.62	0.34
Fat class, ESF[a]	0.17	0.77
Conformation score, units[b]	0.09	0.45
Carcass weight, kg	0.33	1.05
Lamb weaning wt, kg	0.22	1.23

[a]Estimated subcutaneous fat proportions. See footnote for Table A7 for an explanation.

[b]Threshold units on the underlying normal distribution scale. The mean value of 3 for conformation score is transformed to 0 on the underlying normal scale.